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Article (Published Version)

Fialkov, Anastasia and Barkana, Rennan (2019) Signature of excess radio background in the 21-cm global signal and power spectrum. *Monthly Notices of the Royal Astronomical Society*, 486 (2). pp. 1763-1773. ISSN 0035-8711

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Signature of excess radio background in the 21-cm global signal and power spectrum

Anastasia Fialkov^{1,2,3,4,5★} and Rennan Barkana⁶

¹Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

²Department of Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan

³Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK

⁴Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK

⁵Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, UK

⁶Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel

Accepted 2019 March 15. Received 2019 March 14; in original form 2019 February 7

ABSTRACT

The recent tentative detection by the Experiment to Detect the Global EoR Signature (EDGES) low band of the hydrogen 21-cm line from cosmic dawn, if confirmed, is the first ever signature observed from the epoch of primordial star formation. However, the magnitude and the shape of this signal are incompatible with standard astrophysical predictions, requiring either colder than expected gas, or an excess radio background above the cosmic microwave background (CMB) radiation. In this paper, we explore the latter option, investigating possible 21-cm signals in models with standard astrophysics to which a phenomenological excess radio background was added. Assuming uniform radiation with a synchrotron-like spectrum and redshift-independent amplitude existing throughout cosmic history, we show that such a radio background, in addition to explaining the EDGES detection, enhances the cosmic dawn power spectrum. The signal during cosmic dawn and re-ionization strongly depends on both the intensity of the background and the astrophysical parameters. We verify the broad agreement of our models with the detected feature, including additional constraints from the EDGES high-band, high-redshift quasars, and observational limits on the extra-Galactic radio background. The data imply a lower limit on the star formation efficiency of 2.8 per cent, an upper limit on the minimum mass of star-forming haloes of $M_h = 10^9 M_\odot$ at $z = 17$, and a lower limit on the excess background of 1.9 times the CMB at 78 MHz. The properties of X-ray sources are unconstrained by the data. We also show that during the dark ages, such a radio background leaves smoking gun signature in the 21-cm signal.

Key words: galaxies: high-redshift – cosmic background radiation – dark ages, reionization, first stars – early Universe – cosmology: theory.

1 INTRODUCTION

The evolution history of the neutral Universe in the first few hundred million years after the big bang and the process of re-ionization remain poorly constrained. Theoretical modelling bridges between the observations of the 2D surface of recombination at redshift $z \sim 1100$ probed by the cosmic microwave background (CMB) radiation (e.g. Planck Collaboration VI 2018), and the epoch of galaxy formation with the most distant detected galaxy located at $z = 11.1$ (Oesch et al. 2016). Observations of high-redshift dusty galaxies indicate an early onset of star formation. Specifically, recent detection of doubly ionized oxygen at redshift $z = 9.1$ implies a

dominant stellar component that formed at $z \sim 15$ (~ 250 million years after the big bang; Hashimoto et al. 2018). The appearance of massive galaxies of $M_h \gtrsim 10^9 M_\odot$ leads to an efficient re-ionization. The most recent constraints on the neutral hydrogen fraction, $x_{\text{H I}}$, from the damping wings of ULASJ1342 + 0928, a bright quasar at $z = 7.54$ (Bañados et al. 2018), show that the Universe was only 21^{+17}_{-19} per cent neutral at that epoch (at 68 per cent confidence; Greig, Mesinger & Bañados 2018); while the upper limit on the neutral fraction at redshift 5.9 is $x_{\text{H I}} \lesssim 6 + 5$ per cent (at 68 per cent confidence; Greig & Mesinger 2017).

Recently, the first detection of the sky-averaged (global) 21-cm signal of neutral hydrogen from $z \sim 13$ –27 has been claimed based on 2 yr of observations with the low-band antenna of the Experiment to Detect the Global EoR Signature (EDGES) in the 50–100 MHz frequency range (Bowman et al. 2018). If confirmed, this is the

★ E-mail: a.fialkov@sussex.ac.uk

only existing observation from the intermediate redshift range and is the first observational evidence of the primordial star formation at $z \sim 20$ (~ 180 million years after the big bang) and early X-ray heating. This detection is consistent with non-detection of the 21-cm signal at higher frequencies by the EDGES high band (Monsalve et al. 2017, 2018, 2019) and the Shaped Antenna measurement of the background Radio Spectrum2 (SARAS2; Singh et al. 2017; Singh et al. 2018), which indicates that the signal does not vary strongly at redshifts $z \sim 6\text{--}15$. In the framework of standard astrophysical modelling, the data require star formation in small dark matter haloes (Monsalve et al. 2019) and rules out extremely non-efficient X-ray heating sources (Singh et al. 2017; Singh et al. 2018; Monsalve et al. 2019).

The reported cosmological 21-cm signal is centred at $z = 17.2$ (which corresponds to $\nu = 78.2$ MHz), and features an absorption trough of $T_{21} = -500^{+200}_{-500}$ mK, where the error corresponds to 99 per cent confidence including both thermal and systematic noise. The depth of the feature is at least twice as strong as predicted in standard astrophysical scenarios (based on the assumption of Λ CDM cosmology and hierarchical structure formation) where the strongest possible feature at $z = 17$ is -209 mK, assuming the CMB as the background radiation with $T_{\text{CMB}} = 49.5$ K and the coldest possible temperature of the intergalactic medium (IGM) of ~ 7.2 K obtained in the absence of X-ray heating sources. The observed $T_{21} < -300$ mK requires either the gas to be much colder (around 5.2 K) or the background radiation to be much stronger (around 67.2 K), which is hard to explain by astrophysics alone. Finally, no viable model has been proposed to explain the flatness of the best-fitting profile (though the precise shape of the profile may be sensitive to the systematic errors and to the assumed form of the fitted model). Observational effort is underway to test the EDGES low-band signature with global signal instruments including Large Aperture Experiment to Detect the Dark Ages (Price et al. 2018), SARAS3 (variation of SARAS2; Singh et al. 2017; optimized in the 50–100 MHz frequency range), Probing Radio Intensity at high- Z from Marion (Philip et al. 2018); while operating low frequency interferometers (e.g. LOFAR) might be sensitive to the 21-cm power spectrum if it is enhanced accordingly (e.g. Fialkov, Barkana & Cohen 2018).

The frequency of the detected feature can be related to the formation of the first stars that couple the spin temperature to the temperature of the gas via absorption and re-emission of Ly α photons (the Wouthuysen–Field (WF) effect; Wouthuysen 1952; Field 1958). The narrowness of the feature indicates a relatively rapid onset of X-ray heating. Assuming an excess radio background created by high-redshift star-forming galaxies and by trying to match the observed profile, Mirocha & Furlanetto (2018) find that the location of the absorption trough implies efficient star formation in $10^8\text{--}10^{10} M_{\odot}$ haloes and efficient X-ray sources with $f_X > 10$; Kaurov et al. (2018) find that (in the absence of an excess radio background) rapid Ly α coupling is required to reproduce the steepness of the best-fitting profile indicating $M_{\text{H}} \gtrsim 10^9 M_{\odot}$; however, Schauer, Liu & Bromm (2019) show that smaller mass haloes are needed to ensure efficient Ly α coupling at $z \sim 17$.

To explain the depth of the reported feature, exotic mechanisms have to be added to the standard picture. The amplitude of the observed 21-cm feature can be explained by non-gravitational interaction between dark matter and baryons, e.g. via Rutherford-like scattering that could drain access energy from the gas lowering its kinetic temperature (Dvorkin, Blum & Kamionkowski 2014; Tashiro, Kadota & Silk 2014; Muñoz, Kovetz & Ali-Haïmoud 2015; Barkana 2018; Slatyer & Wu 2018). Even though this scenario is

strongly constrained by observations (Barkana et al. 2018; Berlin et al. 2018; Kovetz et al. 2018; Muñoz & Loeb 2018), it is not completely ruled out and is still plausible for a narrow range of parameters including the dark matter mass, electric charge of dark matter particle, and cross-section (e.g. Kovetz et al. 2018). A smoking gun signature of the baryon–dark matter (b–dm) scattering with a velocity-dependent cross-section, first proposed by Barkana (2018) as a solution to the EDGES low-band anomaly, was shown to be an enhanced pattern of baryon acoustic oscillations (BAO) in the 21-cm power spectrum (Fialkov, Barkana & Cohen 2018; Muñoz, Dvorkin & Loeb 2018). The power spectrum itself is boosted by as much as three orders of magnitude that renders the fluctuations detectable by telescopes such as the low-band antennas of LOFAR (Koopmans, private communication).

An excess radio background at the rest frame 1.42 GHz at $z = 17$ would also explain the large contrast observed between the background temperature and the spin temperature of the 21-cm transition (Bowman et al. 2018; Feng & Holder 2018). Astrophysical sources such as accreting supermassive black holes (Biermann et al. 2014; Ewall-Wice et al. 2018) or supernovae (Jana, Nath & Biermann 2018; Mirocha & Furlanetto 2018) could generate the extra radio background via synchrotron emission produced by electrons accelerated in a magnetic field. However, both types of sources would need to be a thousand times more efficient in producing synchrotron radiation than their low-redshift counterparts. Moreover, inverse-Compton cooling off the CMB photons was shown to greatly reduce the efficiency of the radio sources at high redshifts (Oh 2001; Ghisellini et al. 2014; Sharma 2018). An extra radio background can also be created by more exotic processes in which case its intensity is not related to the star formation history. Examples include radiative decay of relic neutrinos into sterile neutrinos (Chianese et al. 2018), models in which additional radiation at 1.42 GHz is injected into the gas via light dark matter decays (Fraser et al. 2018; Pospelov et al. 2018) and superconducting cosmic strings (Brandenberger, Cyr & Shi 2019). Interestingly, evidence of excess radio background above the CMB at low radio frequencies was detected by ARCADE2 at 3–90 GHz (Fixsen et al. 2011) and recently confirmed by LWA1 at 40–80 MHz (Dowell & Taylor 2018). LWA1 measurements are consistent with excess background that can be fitted by a power law with a spectral index of -2.58 ± 0.05 and a temperature of 603^{+102}_{-92} mK at 1.42 GHz. However, it is still not clear what part of the observed excess is extragalactic (Subrahmanyan & Cowsik 2013).

Finally, modification of the thermal history can also be a result of earlier thermal decoupling of baryons from the CMB that can occur as a result of early dark energy (however, such scenarios are ruled out by other observations; Hill & Baxter 2018) or due to an imbalance between the proton and electron number densities (Falkowski & Petraki 2018). Interacting dark energy could modify the evolution of the Hubble parameter and, as a result, affect the 21-cm brightness temperature (Costa et al. 2018); however, in this case the change in the Hubble parameter at $z \sim 20$ would be too large.

In this paper, we use hybrid computational methods to explore the 21-cm signal in models with standard astrophysics (e.g. Cohen, Fialkov & Barkana 2017) to which an excess uniform radio background of redshift-independent amplitude and synchrotron-like spectrum was added. Although this observationally inspired spectrum does not fully represent the above-mentioned realistic scenarios that either generate background with redshift-dependent amplitude and/or a more complicated spectral dependence, it provides a useful guideline. Such a contribution is usually not

considered in 21-cm studies in the literature, where the standard CMB is used as the background (e.g. Mesinger, Furlanetto & Cen 2011). The paper is organized as follows: We outline the methodology and show a few examples of the global signals and the power spectra in Section 2 highlighting the implications of the excess radio background. To explore the dependence of the results on the shape of the radio spectrum, we show several cases with different spectral indexes. We also show that, although the background itself is uniform, it affects the overall level of fluctuations as well as the global signal. In Section 3, we use the reported best-fitting EDGES low-band profile, together with the limits on the 21-cm signal from the EDGES high-band and measurements of $x_{\text{H I}}$, to put constraints on the joint parameter space of standard astrophysics as well as the amplitude of the extra radio background. We discuss the smoking gun signatures of this model and compare them to the signatures of the models with b-dm scattering in Section 4. Finally, we conclude in Section 5.

2 MODELLING

2.1 Thermal and ionization histories

Theory predicts that, as the Universe evolves, astrophysical processes drive major changes in the global thermal and ionization histories. Right after recombination, residual electrons were efficient in coupling the gas temperature to that of the background radiation. As a result, gas and radiation were cooling together at the rate $\propto (1+z)$. However, as a result of the expansion of the Universe, the coupling became inefficient and, at around $z \sim 200$, the cooling rate of the gas increased to $\propto (1+z)^2$. At that epoch, gas was cooling faster than the background. This period in cosmic history, in the absence of luminous astrophysical sources, is called the dark ages and is characterized by a cold and neutral IGM. The emergence of the first stellar and first X-ray populations changed the environment at high redshifts and marked the onset of cosmic dawn. During this epoch, stars produce copious Ly α radiation, and the gas is reheated by the injected X-ray photons that also mildly re-ionize it. The heating rate and the character of fluctuations in the gas temperature depend on the properties of X-ray sources such as the spectral energy distribution (SED) and bolometric luminosity (e.g. Fialkov & Barkana 2014; Fialkov, Barkana & Visbal 2014; Pacucci et al. 2014). The process of re-ionization happens slower than heating as the first small galaxies are thought to be inefficient in ionizing the gas. The appearance of massive galaxies of $M_{\text{h}} \gtrsim 10^9 M_{\odot}$ leads to a more efficient re-ionization that, as observations suggest, starts not long before redshift 7.5 and terminates at $z \sim 6$ (e.g. Greig & Mesinger 2017; Greig et al. 2018). The 21-cm signal is thought to be one of the most promising probes of the global thermal and ionization histories.

2.2 21-cm signal

The 21-cm signal is produced by neutral hydrogen atoms in the IGM. The Hyper-fine splitting of the lowest hydrogen energy level gives rise to the rest frame $\nu_{21} = 1.42$ GHz radio signal with the equivalent wavelength of 21 cm (see Barkana 2016, for a recent review). The cumulative signal of neutral IGM observed against the background radiation depends on the processes of cosmic heating and ionization and, to the leading order, scales as $T_{21} \propto x_{\text{H I}} (1 - T_{\text{rad}} T_{\text{S}}^{-1})$, where T_{rad} is the brightness temperature of the background radiation at 1.42 GHz and T_{S} is the spin temperature of the transition that at cosmic dawn is close to the

kinetic temperature of the gas, T_{K} . Owing to its dependence on the underlying astrophysics and cosmology, this signal is a powerful tool to characterize the formation and the evolution of the first populations of astrophysical sources and, potentially, properties of dark matter, across cosmic time.

The brightness temperature of the 21-cm transition of neutral hydrogen of spin temperature T_{S} observed against background radiation of brightness temperature T_{rad} is given by

$$T_{21} = \frac{T_{\text{S}} - T_{\text{rad}}}{1 + z} (1 - e^{-\tau_{21}}). \quad (1)$$

The 21-cm optical depth is

$$\tau_{21} = \frac{3h_{\text{pl}} A_{10} c \lambda_{21}^2 n_{\text{H}}}{32\pi k_{\text{B}} T_{\text{S}} (1+z) dv/dr}, \quad (2)$$

where $dv/dr = H(z)/(1+z)$ is the gradient of the line-of-sight component of the comoving velocity field, $H(z)$ is the Hubble constant, and n_{H} is the neutral hydrogen number density that depends on the ionization history driven by both ultraviolet and X-ray photons. Usually, a linearized version of equation (1) is used. However, in cases of cold gas temperature the linear expression is not necessarily a good approximation. The spin temperature encodes complex astrophysical dependence

$$T_{\text{S}} = \frac{x_{\text{rad}} + x_{\text{tot}}}{x_{\text{rad}} T_{\text{rad}}^{-1} + x_{\text{tot}} T_{\text{K}}^{-1}}, \quad (3)$$

where

$$x_{\text{rad}} = (1 - e^{-\tau_{21}})/\tau_{21} \quad (4)$$

depends on T_{S} (Venumadhav et al. 2017). To solve for x_{rad} and T_{S} we iterate, starting from the value $x_{\text{rad}} = 1$, until the values of x_{rad} and T_{S} converge. We follow Barkana (2016) to calculate $x_{\text{tot}} = x_{\text{C}} + x_{\alpha, \text{eff}}$ (equations 46 and 48 of Barkana 2016), where $x_{\alpha, \text{eff}} \sim x_{\alpha}$ (equation 57 of Barkana 2016) is the WF coupling coefficient:

$$x_{\alpha} = \frac{4P_{\alpha}}{27A_{10}} \frac{T_{*}}{T_{\text{rad}}} \quad (5)$$

with P_{α} being the total rate (per atom) at which Ly α photons are scattered within the gas and T_{*} is the effective temperature of the 21-cm transition (0.068 K). x_{C} is the collisional coupling coefficient

$$x_{\text{C}} = \frac{n_i \kappa_{10}^i}{A_{10}} \frac{T_{*}}{T_{\text{rad}}}, \quad (6)$$

where κ_{10}^i is the rate coefficient for spin de-excitation in collisions with the species of type i of density n_i , where we sum over species i .

Usually, the background radiation is assumed to be the CMB, $T_{\text{rad}} = T_{\text{CMB}}(1+z)$, where T_{CMB} is the CMB temperature today, 2.725 K. Here, we add a phenomenological uniform excess inspired by the ARCADE2 and LWA1 observations. The total radio background has the form

$$T_{\text{rad}} = T_{\text{CMB}}(1+z) \left[1 + A_{\text{r}} \left(\frac{\nu_{\text{obs}}}{78 \text{ MHz}} \right)^{\beta} \right], \quad (7)$$

where ν_{obs} is the observed frequency, A_{r} is the amplitude defined relative to the CMB temperature, and β is the spectral index.

We solve coupled equations for T_{K} and the free electron fraction, x_{e} , taking into account the following heating and cooling terms: adiabatic cooling, Compton heating (which depends on the total radiation energy density dominated by the CMB), the contribution of X-ray sources (described in Section 2.3), heating by Ly α photons as well as radiative heating that was recently pointed out by

Venumadhav et al. (2017). We account for recombinations and the ionization rate due to X-ray sources. Ionization by stellar ultraviolet photons is implemented separately using the excursion-set approach (Furlanetto, Zaldarriaga & Hernquist 2004).

Fully self-consistent modelling of the 21-cm signal from large cosmological volumes is prohibitively expensive as it requires one both to simulate the distribution of sources and the intensity of radiative backgrounds that fluctuate on scales of a few hundred comoving Mpc and resolve small scales relevant for star and black hole formation. Here, we use hybrid computational methods that track the large-scale evolution on scales above three comoving Mpc while extensively using sub-grid models to account for star formation and the X-ray sources. Our modelling is extensively described in Visbal et al. (2012), Fialkov & Barkana (2014), Fialkov et al. (2014), Cohen et al. (2017), and is partly inspired by the publicly available 21cmFAST (Mesinger et al. 2011). Compared to our previous work, here we improve (1) using the non-linear expression for T_{21} (equation 1), (2) adding the radiative coupling coefficient x_{rad} (equation 4), and (3) accounting for the radiative heating term that contributes about $\mathcal{O}(10)$ per cent of the total heating rate in the scenarios with inefficient X-ray heating (Venumadhav et al. 2017). We replace the CMB background radiation by a more generic frequency-dependent radiative background T_{rad} , equation (7). In addition to the straightforward dependence of T_{21} on T_{rad} in equation (1), the extra radio background affects the calculation of x_{C} and x_{α} .

We use this method to calculate the 21-cm signal in a volume of 384^3 Mpc³ at redshifts from 300 to 6 covering the dark ages, cosmic dawn, and re-ionization. We extract the global signal and the large-scale power spectrum.

In this paper, we assume a homogeneous radio background. However, if radio sources are distributed inhomogeneously around the sky (e.g. due to the clustering of galaxies), fluctuations in the background, δT_{rad} , are imprinted. In this case, the radio background acts as a new source of fluctuations in the 21-cm signal of the form

$$\delta T_{21} = \frac{\partial T_{21}}{\partial T_{\text{rad}}} \delta T_{\text{rad}} = \frac{\tau_{21}}{(1+z)} \frac{-x_{\text{tot}}}{(1+x_{\text{tot}})} \delta T_{\text{rad}}, \quad (8)$$

where for simplicity we assumed $x_{\text{rad}} = 1$, small optical depth τ_{21} , and gas temperature T_{K} independent of the radio background. Such low-frequency radio waves would travel far without significant absorption, so the effective horizon of sources would be set by the time-retarded decline of star formation, modified by the effect of redshift as well as the source radio spectrum. Such fluctuations have not been considered before and will be included in our future work.

2.3 Model parameters

Astrophysical processes affect the 21-cm signal by driving the spin temperature. We include the following processes (see Cohen et al. 2017, for more details):

(i) The Ly α photons produced by stellar sources, couple the spin temperature of neutral hydrogen atoms to the kinetic temperature of the gas (Wouthuysen 1952; Field 1958). Molecular hydrogen cooling allows star formation in small haloes of circular velocity $4.2 < V_{\text{c}} < 16.5 \text{ km s}^{-1}$ ($M_{\text{h}} \sim 10^5 - 10^7 M_{\odot}$) that are abundant at cosmic dawn. However, the H_2 molecule is fragile and star formation in such haloes is suppressed by Lyman–Werner (LW) radiation. Additional inhomogeneous suppression is introduced by the relative velocity between dark matter and baryons (v_{bc} ; Tseliakhovich & Hirata 2010) that imprints the pattern of BAO in the 21-cm signal

(Dalal et al. 2010; Visbal et al. 2012). Higher mass haloes ($V_{\text{c}} > 16.5 \text{ km s}^{-1}$) form stars via atomic hydrogen cooling and are sensitive to neither the LW feedback nor to the effect of v_{bc} . The process of star formation is parametrized by the star formation efficiency, f_* , which we vary in the range $f_* = 0.028 - 50$ per cent and the value of circular velocity that is varied between 4.2 km s^{-1} (molecular hydrogen cooling, corresponding to $M_{\text{h}} = 6.3 \times 10^5 M_{\odot}$ at $z = 17$) and 100 km s^{-1} ($M_{\text{h}} = 8.5 \times 10^9 M_{\odot}$ at $z = 17$), where the high values implicitly take into account various chemical and mechanical feedbacks that we do not include explicitly.

(ii) X-ray sources re-heat the gas after the period of adiabatic cooling. The X-ray spectrum is modelled as a power law with spectral index α that we vary between -1.5 and -1 , lower energy cut-off ν_{min} in the range $0.1 - 3 \text{ keV}$, and normalization constant f_{X} defined via the ratio of the total X-ray luminosity between ν_{min} and 100 keV , L_{X} , to the star formation rate, $L_{\text{X}}/SFR = 3 \times 10^{40} f_{\text{X}} \text{ erg s}^{-1} M_{\odot}^{-1} \text{ yr}$. $f_{\text{X}} = 1$ yields L_{X} normalized to observations of high-redshift X-ray binaries. We explore the range $f_{\text{X}} = 10^{-6} - 10^3$; however, values of $f_{\text{X}} \gtrsim 100$ are unlikely as such a population would saturate the unresolved X-ray background observed by the *Chandra* X-ray Observatory (Fialkov et al. 2017).

(iii) Stellar sources emit ultraviolet radiation that ionizes the gas. Re-ionization is described by the ionizing efficiency of sources, ζ , that at every V_{c} is required to give a CMB optical depth τ in the range between 0.05 and 0.09 , in broad agreement with *Planck* data (e.g. Planck Collaboration VI 2018), and the mean free path of ionizing photons, $R_{\text{mfp}} = 10 - 50 \text{ Mpc}$. The ionizing efficiency has an upper limit of $\zeta < 40000 f_*$ in agreement with stellar models of extreme massive population III stars (Bromm, Kudritzki & Loeb 2001).

(iv) A uniform radio background is added to the CMB and is parametrized by the amplitude A_{r} , calculated at the reference frequency of 78 MHz , and spectral index β as discussed in Section 2.2. We vary the value of A_{r} between 0.3 (0.016 per cent of the CMB at 1.42 GHz) and 2000 (with $A_{\text{r,max}} = 418$ at 78 MHz equivalent to the LWA1 limit, a fraction of 0.22 of the CMB at 1.42 GHz) and assume the fiducial value of $\beta = -2.6$ in agreement with the observed excess found by LWA1 between 40 and 80 MHz . We also show cases with $\beta = -2$ and -3 in Fig. 1.

2.4 Case study

We demonstrate the effect of the extra radio background by comparing the 21-cm global signal and power spectrum for four different cases and show the results in Fig. 1. As a reference, we use a case with no extra radio background ($A_{\text{r}} = 0$) and refer to it as the ‘standard’ astrophysical scenario. The other three examples include a radio background with amplitudes $A_{\text{r}} = 1, 5.7, 18.4$, and different spectral indexes: $\beta = -2, -2.6$, and -3 . Other than A_{r} and β , the astrophysical parameters are fixed: $f_* = 3$ per cent, $f_{\text{X}} = 1$, $V_{\text{c}} = 16.5 \text{ km s}^{-1}$, $R_{\text{mfp}} = 30 \text{ Mpc}$, $\zeta = 14$, and hard X-ray SED with $\alpha = -1.3$, $\nu_{\text{min}} = 1 \text{ keV}$. Even though the assumed radio background is uniform, it affects the fluctuations in the 21-cm signal by affecting x_{α} , x_{C} , x_{e} , and T_{K} .

In our simulations, we assume that this background exists throughout cosmic history, and so it has a large effect on the 21-cm signal (both global signal and the power spectrum) from the dark ages, cosmic dawn, and re-ionization. Its existence during the dark ages would signal the presence of exotic sources (e.g. dark matter annihilation or neutrino decay). If the extra background is generated by stars or stellar remnants, it will only affect the signal from cosmic dawn and re-ionization leaving the dark ages signature

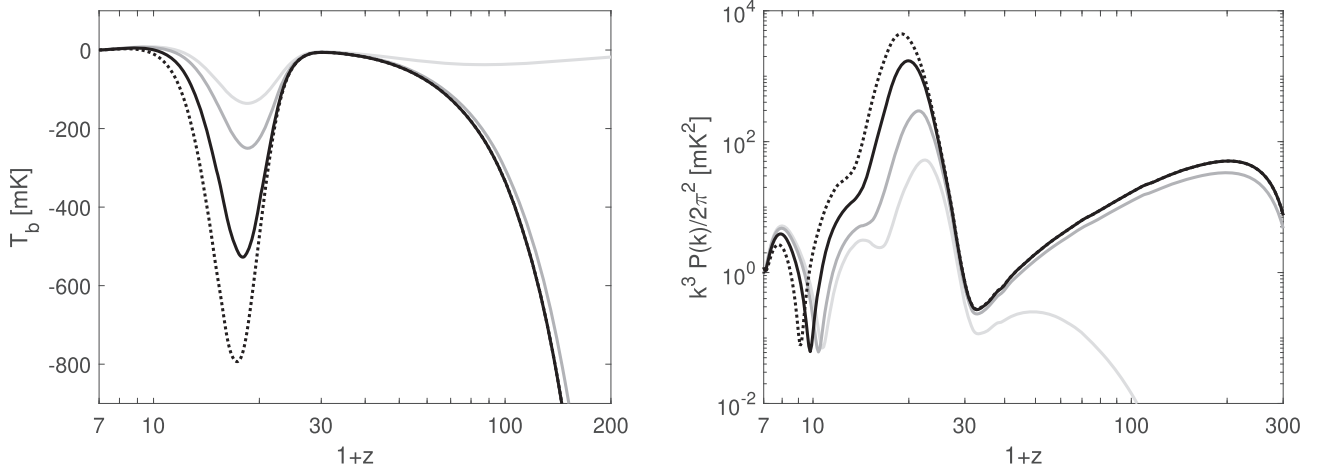


Figure 1. Comparison for the global signal (left) and the power spectrum at $K = 0.1 \text{ Mpc}^{-1}$ (right). We show a case with $A_r = 0$ (light grey), which is the case of ‘standard astrophysics’, and three cases with the extra radio background of $A_r = 1$ and $\beta = -2$ (dark grey), $A_r = 5.7$ and $\beta = -2.6$ (solid black), and $A_r = 18.4$ and $\beta = -3$ (dotted black). All the considered cases assume the same set of astrophysical parameters: $f_* = 3$ per cent, $f_X = 1$, $V_c = 16.5 \text{ km s}^{-1}$, $R_{\text{mfp}} = 30 \text{ Mpc}$, $\zeta = 14$, $\alpha = -1.3$, $\nu_{\text{min}} = 1 \text{ keV}$ (hard X-ray SED).

unchanged. Even though the selected form of the background may not be fully realistic, Fig. 1 demonstrates that changing the spectral index and/or A_r leads to quantitative but not a strong qualitative difference in the signal. Although the dark ages and re-ionization signals rely on the assumption of constant A_r , we expect to see a similar big picture in cases with a redshift-dependent amplitude and a more complicated spectrum. Moreover, as we discuss next, A_r consistent with the EDGES low-band detection will saturate the dark ages signal for $\beta = -2.6$ or steeper spectral indexes leading to model-independent predictions for both the global signal and the power spectrum.

2.4.1 Dark ages

For the selected astrophysical model, the first population of stars forms around $z \sim 30$. At higher redshifts, no stellar Ly α or X-ray photons are present and the only couplings that affect the 21-cm line are due to the interaction with the background radiation or via intra-atomic collisions. In the case with $A_r = 0$, the expected global signal has a weak absorption feature at $z \sim 87$ of $T_{21} \sim -37 \text{ mK}$ and nearly vanishes at lower and higher redshifts due to the CMB coupling. The power spectrum of fluctuations during the dark ages is imprinted by inhomogeneous density and velocity fields as well as fluctuations in x_C , T_K , and x_e and is shown in the right-hand panel of Fig. 1 as a function of redshift at $K = 0.1 \text{ Mpc}^{-1}$. In the standard case, the power spectrum peaks around $z \sim 50$. The only uncertainty in the value of T_{21} from the dark ages arises from the uncertainty in cosmological parameters (which we do not include in our estimates here). An extra radio background changes the global signature and the power spectrum dramatically.

For the values of A_r and β that we show here, the effect of the radio background is saturated (for $A_r = 5.7$ and $\beta = -2.6$ and for $A_r = 18.4$ and $\beta = -3$), or nearly saturated (for $\beta = -2$ and $A_r = 1$), during the dark ages. This can be understood by expressing T_{21} to linear order in T_{rad}^{-1} . For the synchrotron-like background that can explain the EDGES low-band detection, T_{rad} is very large compared to other relevant temperatures at low radio frequencies corresponding to the dark ages, and as a result $x_C < x_{\text{rad}} \sim 1$ (and in the absence of star formation $x_\alpha = 0$). We get $T_{\text{rad}} T_S^{-1} \sim 1 + x_C T_{\text{rad}} / T_K$. Ignoring

the small effect of the radiative heating and because $x_C \propto T_{\text{rad}}^{-1}$, T_{rad} cancels from the expression and we obtain a clear prediction for the 21-cm signal from the dark ages that does not depend on either A_r or β :

$$T_{21}^{\text{lim}} = -\mathcal{N} \frac{n_i \kappa_{10}^i n_H}{(1+z)^2 dv/dr} \frac{T_*}{T_K}, \quad (9)$$

with $\mathcal{N} = 3h_{\text{pl}} c \lambda_{21}^2 [32\pi k_B]^{-1}$. If indeed such an extra radio background exists during the dark ages, the global signal would be enhanced by a factor of ~ 6 at $z \sim 87$, and the power spectrum by a factor of $\mathcal{O}(200 - 300)$ at the same redshift. Owing to the uniquely predicted redshift dependence of a radio-saturated 21-cm signal (equation 9), the nature of the EDGES signal can be easily identified if such a signal is observed, and the strong signal could be used for cosmology.

2.4.2 Cosmic dawn and re-ionization

For the adopted radio spectrum, the intensity is lower at higher frequencies (lower redshifts) and the background is not strong enough to saturate the signal in most of the cases. As a result, astrophysical parameters have an effect and we recover the expected structure of peaks and troughs but with an enhanced or suppressed intensity (Figs 1 and 2); moreover, features are shifted to lower redshifts. The effect of A_r is highlighted in Fig. 2 for two cases: molecular and atomic cooling with fixed astrophysical parameters (see the caption of Fig. 2 for details). Importantly, because the radio background does not produce any feedback on star formation, astrophysical processes (e.g. the build up of the Ly α background) are independent of A_r . However, the value of the coupling coefficient x_{tot} (equations 5 and 6) is lowered by T_{rad} , and, thus, the coupling (defined as $x_{\text{tot}} = 1$) is delayed. In addition, the radiative heating is changed, i.e. the excess radio background results in a higher temperature of the gas (and slightly higher x_e). However, because this effect is small compared to the heating by astrophysical sources, the heating transition (observationally defined as the redshift at which gas heats up to the brightness temperature of the radio background) is still delayed.

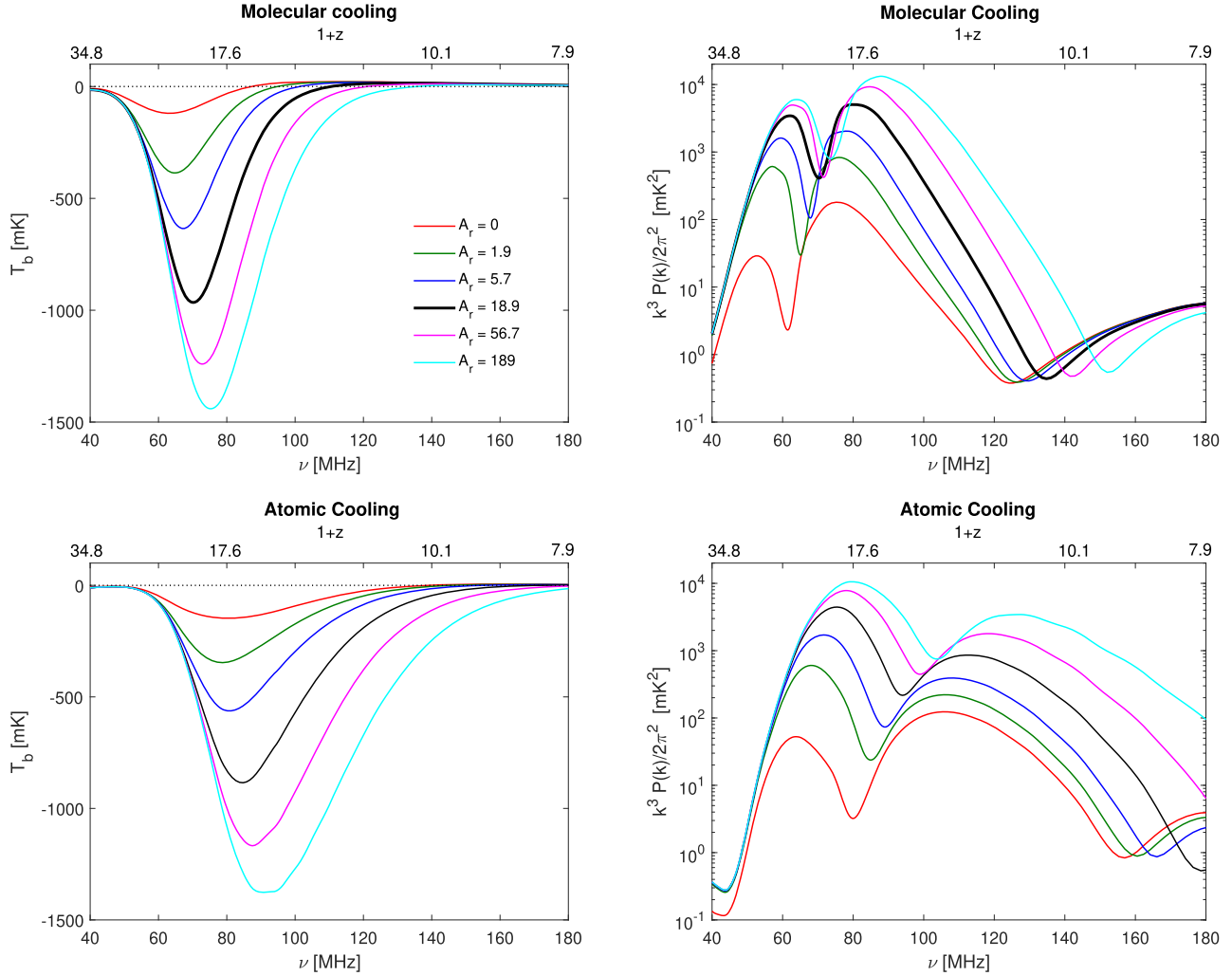


Figure 2. Dependence of the cosmic dawn and re-ionization signals on A_r . We show the global signal (left) and the power spectrum at $K = 0.1 \text{ Mpc}^{-1}$ (right) for the case of molecular cooling haloes (top) with parameters $f_* = 10$ per cent, $f_X = 1$, $V_c = 4.2 \text{ km s}^{-1}$, $\alpha = -1.5$, $\nu_{\min} = 0.1 \text{ keV}$, $R_{\text{mfp}} = 30 \text{ Mpc}$, $\zeta = 11.4$ (which yields $\tau = 0.062$); and atomic cooling haloes (bottom) with parameters $f_* = 3$ per cent, $f_X = 0.1$, $V_c = 16.5 \text{ km s}^{-1}$, $\alpha = -1.5$, $\nu_{\min} = 0.1 \text{ keV}$, $R_{\text{mfp}} = 30 \text{ Mpc}$, $\zeta = 14.2$ (which yields $\tau = 0.064$). The cases are shown for $A_r = 0$ (red), $A_r = 1.9$ (green), $A_r = 5.7$ (blue), $A_r = 18.9$ (black), $A_r = 56.7$ (magenta), and $A_r = 189$ (cyan). The case of molecular cooling haloes with $A_r = 18.9$ (thick black curve, top) is consistent with all the observational constraints discussed in Section 3.

By design, at cosmic dawn the excess radio background generates strong absorption (left-hand panels of Fig. 2). For larger A_r , the absorption feature is deeper, making it easier to observe. However, it is also wider and slightly shifted to higher frequencies (lower redshifts). A corresponding change in the power spectrum is observed (right-hand panels of Fig. 2). The latter is driven by the effect of T_{rad} on the overall global intensity; however, the radio background also separately affects fluctuations in x_α , x_C , T_K , and x_e . As a result of stronger A_r , the Ly α and X-ray peaks are higher and shifted to lower redshifts (higher frequencies).

The same radio background leads to a modification of the re-ionization signature both in the global signal and in the power spectrum. Cases that with weak A_r are seen in emission might appear in absorption for the stronger excess radio background (e.g. the red versus cyan curve in Fig. 2) and the overall intensity of the 21-cm signal might be reduced. This is because the redshift at which T_S reaches T_{rad} (and the signal transits from absorption to emission) is shifted to lower redshifts (deeper into the epoch of re-ionization). In

other cases, e.g. of inefficient heating, an excess radio background tends to enhance the absorption signal during re-ionization.

3 CONSTRAINING ASTROPHYSICAL PARAMETERS WITH EDGES LOW BAND

We use the code outlined in Section 2 to survey the space of astrophysical parameters, varying the parameters relevant for cosmic dawn and re-ionization, namely V_c , f_* , f_X , the X-ray SED, R_{mfp} , and τ as well as the value of A_r , but fixing the spectral index to that of the synchrotron emission $\beta = -2.6$. We randomly probe the parameters, generating a set of 18 309 different models, of which 17 002 models comply with the LWA1 limit.

To verify the consistency of the models with EDGES low-band data, we follow the approach we took in Fialkov et al. (2018) by requiring the signal to be deep, and localized within the band. Within 99 per cent confidence, the cosmological signal should

satisfy

$$300 \text{ mK} < \{\max [T_{21}(60 < \nu < 68)] - \min [T_{21}(68 < \nu < 88)]\} < 1000 \text{ mK}, \quad (10)$$

and

$$300 \text{ mK} < \{\max [T_{21}(88 < \nu < 96)] - \min [T_{21}(68 < \nu < 88)]\} < 1000 \text{ mK}. \quad (11)$$

In addition, we require consistency with the EDGES high-band data (Monsalve et al. 2017) that rule out models with large variations in the 100–150 MHz band and imply

$$|T_{21}(100 \text{ MHz}) - T_{21}(150 \text{ MHz})| < 300 \text{ mK}. \quad (12)$$

In this way, we conservatively demand only rough, overall agreement with the current data. We also assume that $x_{\text{HI}}(z = 5.9) < 20.7$ per cent, which is within 3σ of the value extracted using the dark fraction of quasar spectra (Greig & Mesinger 2017); and $x_{\text{HI}}(z = 7.5) < 71.5$ per cent, which is within 3σ of the neutral fraction measurement extracted from the damping wings (Greig et al. 2018) of ULASJ1342 + 0928, a bright quasar at $z = 7.54$ (Bañados et al. 2018). Finally, we require the extra radio background to be lower than or equal to the observed excess. An example of the signal consistent with all the observational constraints is shown in Fig. 2 (the thick black curve; top panels). Of 17 002 examined models with A_r lower than the LWA1 limit, 1354 models pass the requirement of EDGES low-band data alone, while 686 models pass all the above constraints. The two sets of the global signals and corresponding power spectra are shown in Fig. 3.

As we demonstrated in Section 2.4, for $A_r = 5.7$ and $\beta = -2.6$ the effect of the radio background is saturated during the dark ages, and there is no uncertainty in both the predicted power spectrum and the global signal. As we can see in Fig. 3, this remains valid for all the values of A_r allowed by the data, $1.9 < A_r < 418$. Therefore, if the anomalous EDGES low-band signal is created by exotic physics via an excess radio background, the dark ages could potentially confirm this origin (for models in which the radio background was present at such early times). However, at lower redshifts, during cosmic dawn and re-ionization, the allowed models show a lot of variety as a result of the interplay between the radio background and other astrophysical parameters. Both the global signals and the power spectra are boosted at $z \sim 17$, with an enhancement in the squared fluctuation of up to $\mathcal{O}(100)$ compared to the strongest allowed signals with $A_r = 0$ (the dashed blue curve in Fig. 3 shows the envelope of all the cases with no radio background for comparison). During re-ionization, the signals that with T_{CMB} would be seen in emission are mostly suppressed because the stronger background radiation leads to a weaker contrast between T_{rad} and T_K . Even with the suppression, however, all the considered scenarios are within reach of the Square Kilometer Array (SKA; the predicted power spectrum sensitivity curve is shown in cyan; Koopmans et al. 2015).

Existing observations allow us to constrain astrophysical parameters of cosmic dawn. In Fig. 4, we show the values of astrophysical parameter for the 686 models consistent with all the observational constraints (the black circles; complying with EDGES low-band, EDGES high-band, quasars, and LWA1 constraints) and the 1354 models consistent with the EDGES low-band and LWA1 data (the grey crosses) along six different cuts of the explored parameter space, namely f_* – f_X , f_* – V_c , f_X – V_c , A_r – f_X , A_r – V_c , and A_r – f_* . Next, we summarize the astrophysical constraints.

3.1 Excess radio background

Our analysis shows that the models consistent with the above-mentioned constraints share high values of the amplitude of the radio background, $A_r > 1.9$ at the reference frequency of 78 MHz (equivalent to 0.1 per cent of the CMB at the reference frequency of 1.42 GHz). Of the explored range $0.3 < A_r < 2000$, the values between 1.9 set by the EDGES low-band detection and the absolute upper limit $A_{r,\text{max}} = 418$ set by the LWA1 observation are allowed. However, there is a degeneracy between the values of A_r and f_X (lower left-hand panel in Fig. 4) because the two parameters affect the depth of the absorption feature. We find that for values of f_X much higher than unity for which the absorption trough in the absence of the radio background is very shallow (the shallowest absorption trough found in the recent parameter study by Cohen et al. 2017 is of -25 mK), higher values of A_r are allowed by the EDGES low-band data with the maximal value fixed by the LWA1 observation and a slightly elevated lower limit of ~ 4 . For low values of f_X , the absorption trough is deep even for $A_r = 0$ (the deepest absorption trough found in the parameter study by Cohen et al. 2017 is of -240 mK). Therefore, the maximum allowed A_r decreases as f_X decreases. For $f_X \ll 1$, X-ray sources have a very weak effect on the 21-cm signal, and the allowed range of A_r is independent of f_X : $1.9 < A_r \sim 25$ with EDGES low-band constraint only and $1.9 < A_r \sim 5.8$ when the lower redshift constraints are included. (Note that the limits that we derive here depend on the spectral index. The values of A_r are expected to be higher for more negative β in agreement with the trend in Fig. 1).

The minimum required value of $A_r = 1.9$ may seem somewhat high compared to the value ~ 1 expected based simply on the minimum absorption depth measured by EDGES. The reason is that the EDGES measurement gives a combination of constraints, requiring the high-redshift feature to be deep and narrow at the same time. The narrowness of the measured absorption feature, and the limited frequency range of the entire EDGES measurement, implies that in some models only part of the total absorption feature is captured within the EDGES low band. In these cases, the entire profile is wider and deeper than the reported signal, and higher values of A_r are needed to explain the observed contrast.

3.2 X-ray heating efficiency

It was recently shown that, in the absence of an excess radio background, non-detection of the 21-cm signal by EDGES high band places a lower limit of $f_X = 0.0042$ (Monsalve et al. 2019). Based on the compilation of models examined in this paper, we find that, owing to the contribution of the excess radio background, no values of f_X are ruled out by the low-redshift data¹

We find that the data do not constrain f_X , and the only condition on f_X is imposed by the degeneracy with A_r described above: at values of A_r higher than ~ 25 only $f_X \gtrsim 1$ are allowed because the lower values of f_X would generate steeper (and deeper) than observed signals. At lower values of A_r , lower values of f_X are allowed (in agreement with the lower left-hand panel of Fig. 4). Finally, at the lowest possible A_r , $f_X \gtrsim 0.1$ are excluded as they would create a shallower than detected absorption feature.

¹However, only a qualitative comparison can be made here with the results of Monsalve et al. (2019), where a much more rigorous data analysis and joint fitting of the modelled 21-cm signals and foregrounds to the data were performed.

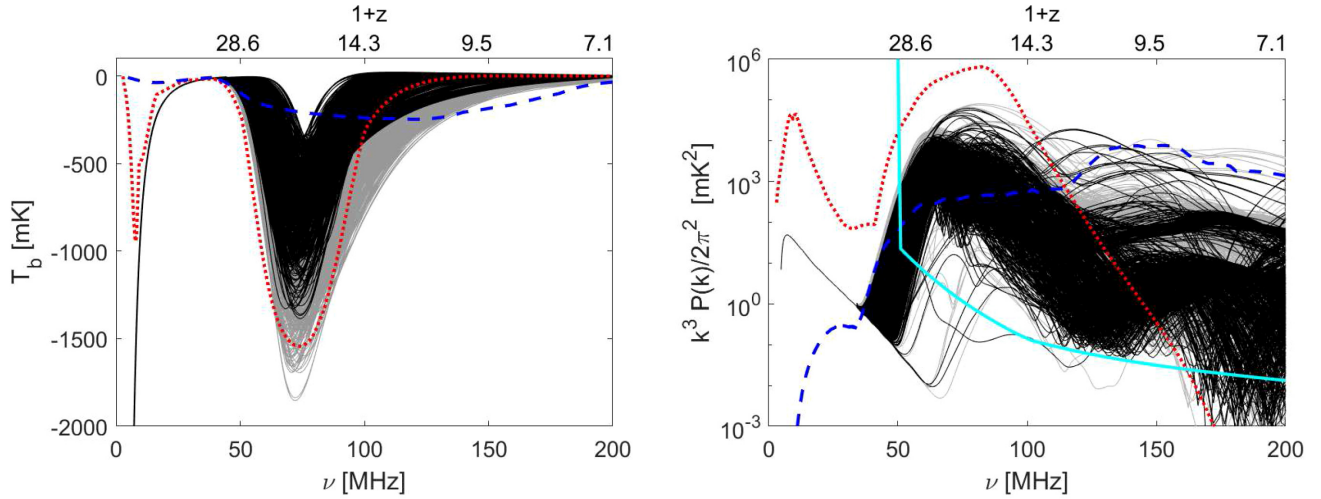


Figure 3. Summary of models. We show the global signal (left) and the power spectrum at $K = 0.1 \text{ Mpc}^{-1}$ (right) versus frequency/redshift (bottom/top). Models that are compatible with EDGES low band and are also allowed by the LWA1 data are shown in grey (1354 cases); models compatible with EDGES low-band, high-band, high-redshift quasars at $z = 5.9$ and $z = 7.5$ and are also allowed by the LWA1 data are shown in black (686 cases); the upper limit on T_{21} and on the power spectra for models that do not include the extra radio background ($A_r = 0$) is shown in the dashed blue line. The dotted red line shows the upper limit for models with b-dm scattering, which are discussed in Section 4 (the red, valid models in Fialkov et al. 2018); we note that this line includes fluctuations only due to the b-dm scattering and does not include astrophysical sources of fluctuations. On the power spectrum plot, we also show the SKA1 noise curve (solid cyan).

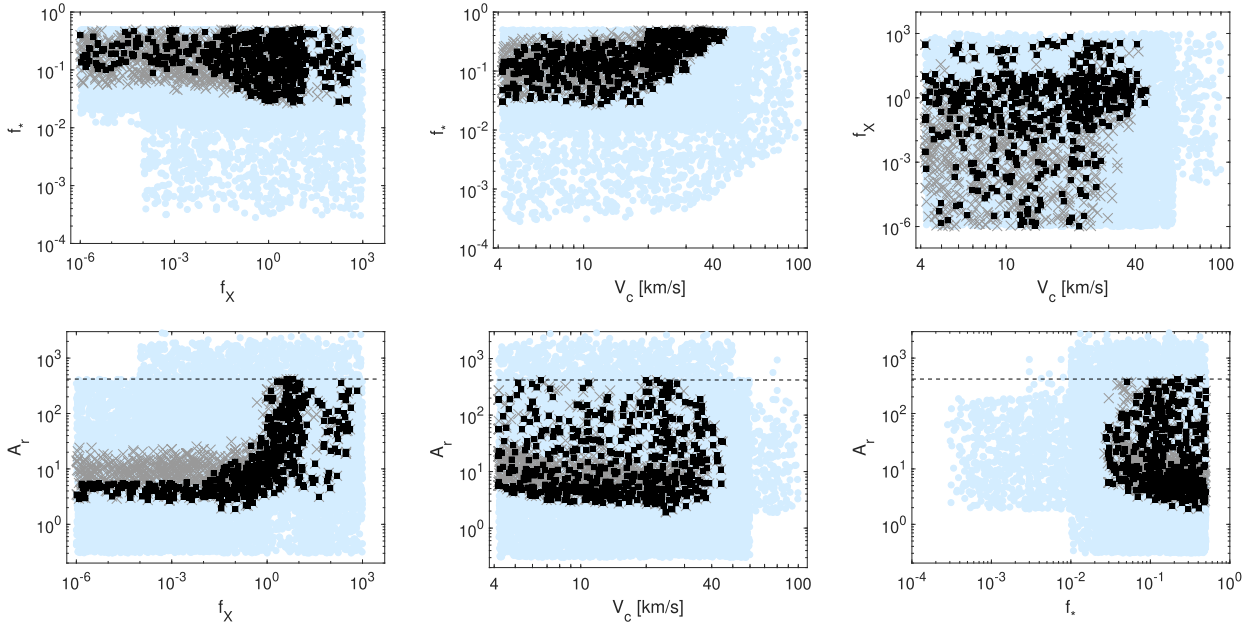


Figure 4. Astrophysical parameter space of allowed models that are compatible with EDGES low-band data and the LWA1 data (1354 cases; the grey crosses); models compatible with EDGES low-band, high-band, high-redshift quasars at $z = 5.9$ and $z = 7.5$ and the LWA1 data (686 cases; the black dots). The blue dots show the entire parameter space surveyed in this study as specified in Section 2.3, 18 309 models in total. The dashed line (bottom panels) shows the LWA1 limit.

Our conclusion is different from the results of Mirocha & Furlanetto (2018) who placed a lower limit of $f_X = 10$. This is because Mirocha & Furlanetto (2018) required the signal to be entirely within the band and the total absorption to match the observed trough in absolute depth; while our equations (10), (11), and (12) imply that in some cases only part of the total absorption profile is within the EDGES low band. In addition, Mirocha & Furlanetto (2018) considered models in which the radio background is tied to the star formation history.

3.3 Star formation efficiency and mass of star-forming haloes

$\text{Ly}\alpha$ coupling governs the high-redshift end of the cosmic dawn signal and, regardless of f_X , is constrained by the EDGES low-band observation that requires intense star formation before $z = 17$. The efficiency and timing of the coupling are determined by f_* and V_c together.

Using the non-detection of the 21-cm signal with the EDGES high-band data, Monsalve et al. (2019) excluded intermediate

values of f_* between 0.4 per cent and 3.9 per cent and found degeneracy in the f_*-f_X , f_*-V_c , and V_c-f_X planes. The detection in the low-frequency band adds a new constraint. Of the considered range, 0.01 per cent $< f_* < 50$ per cent, only $f_* > 2.8$ per cent is consistent with the data. Lower values of f_* result in a wide absorption feature that is shifted to lower redshifts and would be outside the observed 50–100 MHz band. This lower limit is nearly independent of f_X or A_r , but strongly depends on V_c at halo masses above the atomic cooling threshold. This is because for high values of V_c the absorption trough shifts to lower redshifts and outside the EDGES low band and only very high values of f_* can compensate for this trend and shift the signal back to higher redshifts. Below atomic cooling, feedback limits the contribution of small haloes. Also, considering the high- and the low-redshift constraints together gives a dependence of the minimum value of f_* with f_X .

We find that, of the considered range $4.2 < V_c < 100 \text{ km s}^{-1}$ (or equivalently $6.3 \times 10^5 < M_h < 8.5 \times 10^9 M_\odot$ at $z = 17$), the values of V_c between 4.2 and 45 km s^{-1} (i.e. $M_h < 7.8 \times 10^8 M_\odot$ at $z = 17$) are allowed. The maximum V_c is set by our upper limit on f_* of 50 per cent. If, e.g. we were to only allow f_* up to 10 per cent, the maximum V_c would then be 30 km s^{-1} ($2.3 \times 10^8 M_\odot$ at $z = 17$). This limit is consistent with what is reported by Mirocha & Furlanetto (2018) and Schauer et al. (2019) who found that star formation in haloes below $10^8 M_\odot$ is required to explain the EDGES low-band signal. In addition, non-detection of the signal by the EDGES high-band separately requires the existence of small star-forming haloes of $M_h < 1.3 \times 10^8 M_\odot$ (Monsalve et al. 2019).

4 DISCUSSION

Scenarios that we have explored here intend to explain the deep absorption signal detected by EDGES low band via an excess radio background. Another set of models proposed in the literature as a solution to the EDGES low anomaly are the models with non-gravitational b-dm scattering (Barkana 2018). Here, we point out major differences between the two types of signature.

In Fig. 3, we show the envelope of all signals with b-dm scattering that comply with the EDGES data (the red curves), which we explored in Fialkov et al. (2018). This set of models explores the full astrophysical parameter space, to which dark matter mass and scattering cross-section were added. The models assume a velocity-dependent cross-section of the form $\sigma \propto v^{-4}$ and that 100 per cent of dark matter scatter off baryons. Even though scenarios in which 100 per cent of the dark matter interacts are ruled out by observations (Barkana et al. 2018; Berlin et al. 2018; Muñoz & Loeb 2018), non-gravitational scattering of baryons off dark matter is still a plausible scenario assuming that only a few per cent of dark matter bears electric charge of a few times 10^{-6} of the charge of an electron. Such scenarios can still be realized (with properly re-scaled cross-section) and it is still interesting to point out smoking gun signatures of the two classes of models. We also note that other particle physics scenarios are still being explored (e.g. Falkowski & Petraki 2018; Houston et al. 2018).

In the absence of astrophysics, the dark ages provide a unique environment to constrain exotic physics. The global signal in the case of b-dm scattering features a deeper trough than the one expected from the standard case (i.e. $\sigma = 0$ and $A_r = 0$), the blue line in Fig. 3 shows the envelope of such models); while in the cases with $A_r \neq 0$ the signal grows with increasing redshift (as long as the radio background has already appeared). Because the radio background itself is assumed to be uniform, fluctuations are not as

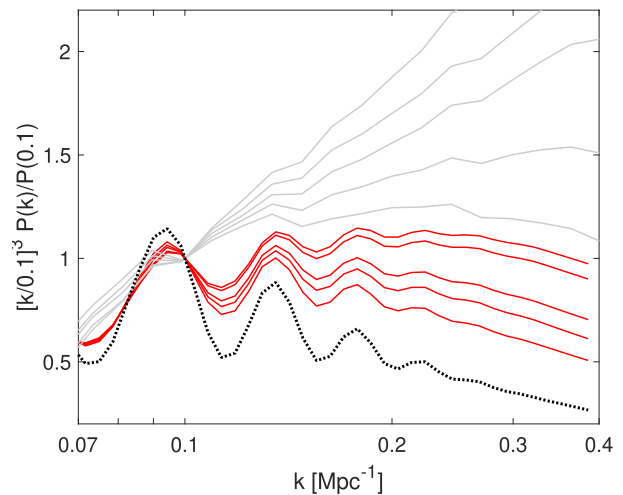


Figure 5. Spectral shape with an excess radio background (grey) and b-dm scattering (red) at $z = 17$. A few randomly chosen models are shown to illustrate each category of models. The shape of the power spectrum of the b-dm relative velocity is also shown (dotted black).

high as those that are possible in the b-dm scattering case where the power is boosted by the velocity-dependent cross-section.

At cosmic dawn and re-ionization, the signatures of both the radio background and the b-dm scattering are contaminated by astrophysical processes and it would be harder to uniquely establish the nature of the enhancement in the global signal. However, the expected power spectra bear unique signatures and are key to identifying the nature of the enhancement. Because of the velocity-dependent cross-section, in the case of b-dm scattering the power spectrum is (1) enhanced by up to four orders of magnitude compared to the standard case, and (2) bears a unique signature of BAO imprinted by the relative velocity between dark matter and gas, v_{bc} (see Section 2.3). Examples of BAO at $z = 17$ in the spectral shape, illustrated using the ratio of the power spectrum in mK^2 units ($k^3 P(k)/2\pi$) to its value at $K = 0.1 \text{ Mpc}^{-1}$, are shown in Fig. 5 as a function of the comoving wavenumber. For comparison, the enhancement in the power spectrum in the case of $A_r \neq 0$ is weaker (only up to two orders of magnitude higher than the standard astrophysical scenarios, compared to four orders of magnitude in the b-dm case), and the spectral shape does not feature BAO.

5 SUMMARY

In this paper, we have examined the effect of a uniform radio background, existing in addition to the CMB, on the 21-cm signal from the dark ages, cosmic dawn, and re-ionization, assuming a synchrotron-like spectrum of spectral index $\beta = -2.6$ and redshift-independent amplitude. We demonstrate both the global signal and the power spectrum computed in the 6–300 redshift range. We vary conventional astrophysical parameters as well as the amplitude of the extra radio background and put limits on astrophysical parameters by requiring the broad consistency of models with the data of EDGES low-band, EDGES high-band, limits on $x_{\text{H I}}$ from quasars at $z = 5.9$ and 7.5 as well as the observed excess of the radio background detected by LWA1 between 40 and 80 MHz. Finally, we point out that a non-uniform radio background would add a new source of fluctuations that are unaccounted for in present-day 21-cm codes.

The effect of an extra radio background is to deepen and widen the absorption trough. We find that the reported global signal at low frequencies is consistent with values of the amplitude of the excess radio background of $1.9 < A_r < 418$ relative to the CMB at the 78 MHz reference frequency of cosmic dawn (corresponding to 0.1–22 per cent of the CMB at 1.42 GHz). The EDGES low-band detection requires efficient star formation ($f_* > 2.8$ per cent) occurring in small haloes with circular velocity below $V_c = 45 \text{ km s}^{-1}$ (corresponding to $M_h < 7.8 \times 10^8 M_\odot$ at $z = 17$). We find that for high V_c higher values of f_* are required. This measurement alone does not place bounds on f_X . The only constraint is that at high A_r higher values of f_X are required to fit the data. Adding the low-redshift data (quasars, EDGES high band) restricts the range of the allowed values of A_r ; however, contrary to what is found with the low-redshift data alone (Monsalve et al. 2019), there is no lower bound on f_X . Finally, we find degeneracy in the V_c – f_X , V_c – f_* , and V_c – f_* planes, in broad agreement with the joint analysis by Monsalve et al. (2019) of the EDGES high-band data and quasar and Lyman-break galaxies data.

The 21-cm fluctuations during cosmic dawn are increased correspondingly to the global signal, while fluctuations from the epoch of re-ionization are either suppressed or enhanced depending on the parameters. Compared to the case of b–dm scattering that features strong BAO due to the velocity-dependent cross-section, the spectrum in the case of the extra radio background has a smooth shape and is not as strongly enhanced on large scales. Low-frequency observations with interferometers such as LOFAR, HERA, and, once operational, the SKA, will be able to test the detection by the EDGES low band and, if confirmed, assess the nature of the enhancement via the magnitude of the fluctuations and the presence or absence of the BAO.

Finally, we find that the signal from the dark ages can be used to identify the origin of the EDGES low-band signal and is the unique discriminator of the signature of the radio background (if the radio background is already present at such early times) versus scenarios such as b–dm scattering. If the extra radio background is realized in Nature and is present prior to the onset of star formation, the dark ages signal will be enhanced. We find that any A_r that explains the EDGES low-band detection will saturate the dark ages signal for $\beta = -2.6$ or steeper spectral indexes. In this case, the dark ages signal (both the global signal and the power spectrum) is model independent and has a unique redshift dependence. Several satellite missions are being discussed to detect the 21-cm signal from the dark ages that will enable us to test the presence of the radio background at lower frequencies and, if the anomalous signature is detected, verify its origin (e.g. Burns et al. 2019).

ACKNOWLEDGEMENTS

We acknowledge the usage of the Harvard *Odyssey* cluster. Part of this project of AF was supported by the Royal Society University Research Fellowship. This project/publication was made possible for RB through the support of a grant from the John Templeton Foundation. The opinions expressed in this publication are those of the authors and do not necessarily reflect the views of the John Templeton Foundation. RB was also supported by the ISF-NSFC joint research program (grant No. 2580/17).

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